Extracting Smart Contracts Tested and Verified in Coq

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Motivation: smart contracts

Smart contracts (SCs):

programs in a general-purpose language running "on a blockchain"

Blockchain $\sim$ database, smart contracts $\sim$ stored procedures.

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What is so special about them?

- Manage money: auctions, crowdfunding, multi-signature wallets, ...
- Immutable.
- Code is Law.
- Call other (possibly malicious) contracts.
- Flaws may result in huge financial losses:
  - The DAO $\sim$ \$50M — hacker attack.
  - Parity's multi-signature wallet $\sim$ \$280M — bugs in the library code.

Functional smart contract languages

- Contracts are (partial) state transition functions:

```
contract : CallCtx * Msg * State -> option (State * Action list)
```

- A *scheduler*
  - updates the state;
  - handles transfers and calls to other contracts in `Action list`.

Examples of such languages:
LIGO (Tezos), Liquidity (Dune), Scilla (Zilliqa), Sophia (Æternity), etc.

From Coq to blockchain

- Smart contract verification is crucial.
- Coq is well-suited for functional smart contracts.
- We want to do all the development in Coq.
- Use ConCert for verification.[1]

[1] DA, Jakob Botsch Nielsen, and Bas Spitters. ConCert: A Smart Contract Certification Framework in Coq. CPP'2020

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Solution: Code extraction!

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Extraction in Coq

- Supports extraction to OCaml, Haskell and Scheme.
- General idea: turn computationally irrelevant bits into □ (a **box**).
- Proofs (propositions) and types appearing in terms become boxes.
- The underlying theory: Pierre Letouzey's PhD thesis.

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- Proofs (propositions) and types appearing in terms become boxes.
- The underlying theory: Pierre Letouzey's PhD thesis.
- ✗ Not directly suitable for targeting:
  - functional smart contract languages;
  - functional fragments of multi-paradigm languages (e.g. Rust)
- ✗ Current Coq extraction is not verified.
- ✓ MetaCoq erasure is verified!

The MetaCoq project

MetaCoq: Formalising Coq in Coq

Consists of several subprojects.

- Template Coq — adds meta-programming facilities to Coq:
  - reflects Coq's kernel;
  - quote/unquote.
- PCUIC (Predicative Cumulative Calculus of Inductive Constructions) — meta-theory of Coq.
- Safe Checker — verified reduction machine, conversion checker and type checker for PCUIC.
- **Erasure** — a verified erasure procedure.[2]

[2] Matthieu Sozeau, Simon Boulier, Yannick Forster, Nicolas Tabareau and Théo Winterhalter. Coq Coq correct! verification of type checking and erasure for Coq, in Coq.

MetaCoq's verified erasure

- A translation from PCUIC (the calculus of Coq) into $\lambda\Box$, untyped lambda-calculus with an additional constant $\Box$.
- Provides a proof that the evaluation of the original and the erased terms agree.

Missing bits for practical use:

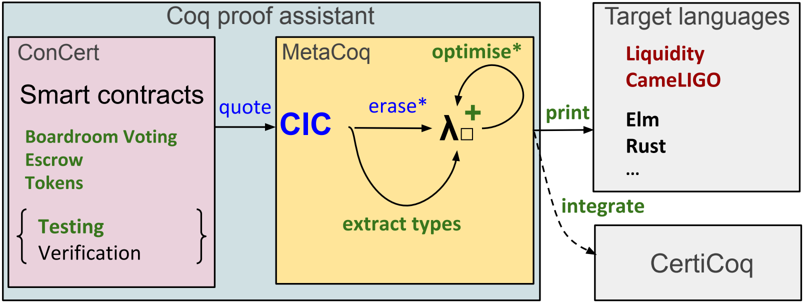
- No erasure for types and inductives.
- Requires more optimisations (e.g. removing boxes).

Contributions

- Real-world SC implementations:
  - Boardroom Voting.
  - Escrow.
  - Implementation of tokens: EIP/ERC-20, FA2.
- Testing SCs for preliminary bug discovery.
- Executable code generation through extraction.
- Verified optimisations of extracted code.
- Code extraction useful for various targets, not only smart contracts.

The pipeline

In **green** — our contributions.
Transformations marked with * — verified.



TCB: the usual of Coq + MetaCoq quote + printing + target language.

Our extraction

We extend MetaCoq:

- Extraction of types and data type definitions
  (crucial for targeting typed languages)
- A verified optimisation procedure:
  - removes unused arguments of functions;
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On top of this — pretty-printing to various targets.

Challenges of new targets

- No `Obj.magic`/`unsafeCoerce` (only available in Rust)
- Non-recursive data types only — Liquidity, CameLIGO.
- Limited support for recursion (e.g. tail recursion only, or no direct access to recursion — only through primitives) — Liquidity, CameLIGO.

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Consequences:

- Some extracted code will not be well-typed.
- Remapping (cf. `Extract Inlined Constant`) is mandatory for some recursive definitions
  (also crucial for performance on a blockchain)

Deboxing

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    @map nat nat (fun x : nat ⇒ x ∗ x) xs.
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Deboxing — a transformation that removes redundant boxes.

When (and why) is it safe to remove boxes?

- Constants: after unfolding `(fun x ⇒ t) v` $\sim$ `t`, if `x` is not free in `t`
- Deboxing is a special case: `(fun A x ⇒ t)` $\square \sim$ `(fun x ⇒ t)`.
- Constructors: boxes don't carry any useful information.
- We remove boxes from applications of constants and constructors.

The "dearging" optimisation

De-arging: removing the "dead" arguments

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Optimises to

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Consists of two stages:

- Analysis: generate masks for constants and constructors (e.g. for `foo`: mask = `[f;t;t]`).
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Note:

- if a constant or constructor is not applied "enough" — η-expand.
- With η-expansion, it might not be an optimisation.

Soundness theorems

Soundness wrt. a big-step call-by-value evaluation relation $\Sigma \vdash t \triangleright v$

Theorem (Soundness of dearging)

Let Σ, t *be a valid environment and a term of* $\lambda\Box$, η-**expanded according to provided masks**, *then*

$\Sigma \vdash t \triangleright v$ *implies* $\texttt{dearg\_env}(\Sigma) \vdash \texttt{dearg}(t) \triangleright \texttt{dearg}(v)$

Theorem (Soundness of extraction)

Let Σ *be a valid CIC environment,* C *a constant in* Σ, Σ', C *— an environment and a constant after extraction and optimisations, then*

$\Sigma \vdash_p C \triangleright Ctor$ *implies* $\Sigma' \vdash C \triangleright Ctor$

We get the η-expansion premise in a *certifying* way: quote a term, expand it, unquote back and generate a proof.

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Guarantees (given the TCB):
extracted program type checks $\longrightarrow$ gives the same result as the original.

A counter contract

```
Inductive msg :=
  Inc (_ : Z)
| Dec (_ : Z).

Definition storage := Z.

Definition pos := {z : Z | 0 <? z}.

Program Definition inc_counter (st : storage) (inc : pos) :
  {new_st : storage | st <? new_st} := st + inc.
Next Obligation. (* proof omitted *) Qed.
...

Program Definition counter (msg : msg) (st : storage) : option storage :=
  match msg with
  | Inc i ⇒ match (bool_dec (0 <? i) true) with
            | left h ⇒ Some (inc_counter st (exist i h))
            | right _ ⇒ None
            end
  | Dec i ⇒ ...
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Extracted code

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type Msg
  = Inc Int
  | Dec Int

type alias Storage = Int

type Sig a = Exist a

type alias Pos = Sig Int

proj1_sig : Sig a → a
proj1_sig e = case e of Exist a → a

inc_counter : Storage → Pos → Sig Storage
inc_counter st inc = Exist (add st (proj1_sig inc))
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counter : Msg → Storage → Option Storage
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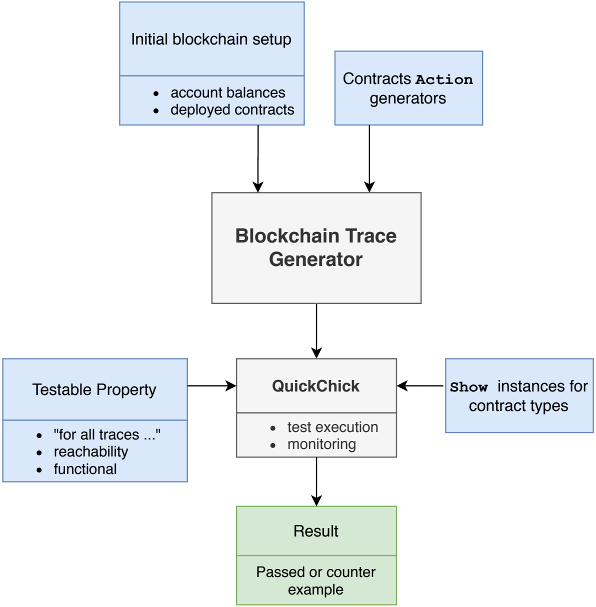
"Logical" bits are erased

Listing 1: Elm

Experience with extraction

- We have extracted several SCs:
  counter, crowdfunding, prototype DSL interpreter, escrow.
- Extraction to Elm:
  list functions from Coq's stdlib, counter, `safe_head` (false elim), the Ackermann function (well-founded recursion).
- Liquidity and CameLIGO have many restrictions, requres remapping.
- Elm is closer to $\lambda\square$, extraction is more principled.
- Rust: several examples from Coq's stdlib, small examples with dependent types, graph coloring (from the CertiCoq benchmark) — WIP.

Overview of the Testing Framework



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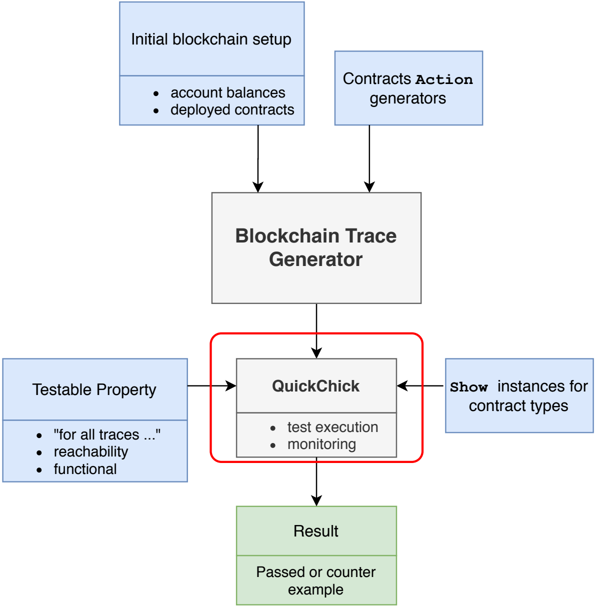

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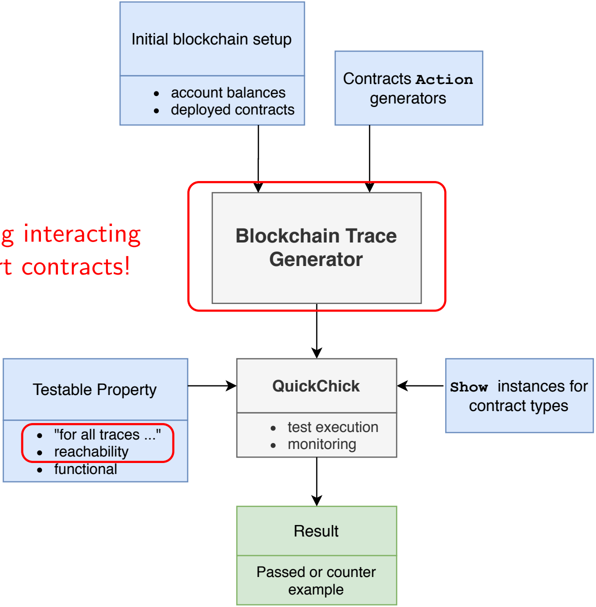
Testing interacting smart contracts!



Testing Smart Contracts

- Cost-effective, semi-automated approach to discover bugs.
- Allows for finding bugs earlier, helping the verification efforts.
- The first to support testing on execution traces.
- Case studies: Tokens (ERC20, FA2), Escrow, Congress, UniSwap.
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Tricky bits

- Requires specialised generators defined manually (otherwise too many discards).

More smart contracts in ConCert

- Boardroom voting
  - computes a public tally from private votes;
  - tallying is based on finite field arithmetic;
  - verified, extraction — WIP.
- Escrow
  - a common contract in "decentralised finance" (DeFi);
  - tested, verified and extracted.
- Tokens
  - widely used to represent various assets;
  - tested and extracted.

Conclusions and Future work

- Practical use of the MetaCoq's erasure, thanks to our extensions.
- Verified optimisations of the extracted code.
- A step towards verified extraction framework.
- New extraction languages: Liquidity, CameLIGO, Elm and Rust.
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What's next?

- More optimisation passes.
- Inserting type coercions, if supported by a target language.
- Change erasure to remove the "applied box" problem.

Thank you!